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DYNAMIC BEHAVIOR OF JET ENGINES WITH AIR EXTRACTION BEHIND THE COMPRESSOR

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ABSTRACT

A procedure to describe the dynamic behavior of jet engines with particular respect of interferences is /17* presented. Starting with the thermodynamic relationships and the flow behavior of the individual structural groups of the engine, it is feasible to determine the transfer functions of all engine parameters. The dynamic behavior of a turbojet engine without controls, particularly as affected by interferences due to compressor air extraction, is described in detail. The progress of the data essential to the operating safety of the engine can be followed. The results obtained subsequently permit the investigation of engines with control systems.

Outline

*Numbers given in the margin indicate the pagination in the original foreign text.

1. Introduction

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In some VTOL aircraft designs, air is ejected through control jets to stabilize the flight position during the starting, transition and landing phases (e.g. Short SC1 and Dassault Balzac V-001). The jets are arranged as far as possible from the center of gravity of the aircraft in order to keep the mass output required to achieve the necessary steering moment at a minimum. The supply of compressed air must be provided by the engines which are thus subjected to additional requirements. Depending on the size of the aircraft, certain quantities of air are taken for short period of time, irregularly, in a stationary or dynamic manner from one or more engines. The volumes taken may amount at maximum to 15% of the air flow through the compressor.

Safety in operation and the achievement of the expected life of engines can be guaranteed only if several criteria, such as limited rpm, maximum gas temperature before and after the turbine and maximum duct-wall temperatures, also stable operation particularly of the compressor, are accurately observed. If the engines are carrying additional loads, e.g. by taking air from them, the conditions are no longer satisfied. One cannot predict immediately in what fashion and to what extent the number of revolutions, the most important operating temperatures and the position of the operating point in the characteristic field of the compressor will be changed by the ejection of air. Further, it is not sure how these operating data will vary during nonstationary air ejection. The purpose of the present study is to investigate the dynamic behavior of turbojet engines in the case of the disturbance caused by air extraction after the compressor.

2. Engine and Control

2.1 Closed control circuit

The engine and the regulator form a closed control circuit. The diagram in Fig. 1 gives a simplified idea of the interaction of the two components. The regulator is frequently designed in the form of multiple controls, which in addition to the governing factor w, i.e. the setting of the control lever, accept several control factors x_1, x_2 .... (e.g. number of revolutions n, pressures p_{1t} and p_{2t}, also the gas temperature T_{4t}) as the input. Correspondingly, several controlled /set/ factors y_1, y_2 ... (e.g. fuel supply to the main and after-burner chambers $\dot{Q}_C$ and Q_{PC} and the thrust jet cross section A_D) are available. Occasional interferences z_1, z_2 .... (e.g. air extraction flow B, Mach number M_{∞} and environmental conditions p_∞ and T_∞) constitute together with the controlled factors the input values of the engine.

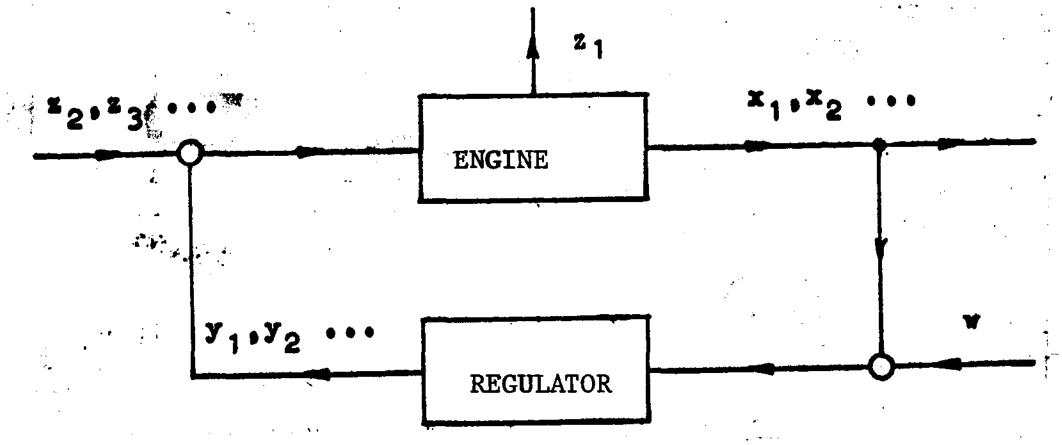


Figure 1. Diagram of the Control Circuit

w	Governing factor	Setting of control lever
x_1, x_2,...	Control factors	e.g. number of revolutions, pressures P_{it}; P_{2t}, the gas temperature T_{4t} and other dependent variables.
y_1, y_2...	Controlled factors	e.g. fuel flows $\dot{Q}_C$ and $\dot{Q}_{PC}$, thrust jet cross section A_D
z_1, z_2...	Interferences	e.g. flow of extracted air $\dot{B}$, Mach number $_\infty$, environmental conditions P_∞ and T_∞.

2.2 Control Train /3

The characteristics of the engine are generally given and firm, while the regulator may be designed to provide favorable control behavior. A prerequisite of the design of the regulator is accurate knowledge of the dynamic behavior of the control train, i.e. the engine. The problem therefore initially consists of the formulation of all necessary and relevant relationships between the dependent variables of the engine, some of which are used as controlled factors, and the independent variables, i.e. the governing factors and the interfering magnitudes, if present. Fig. 2 presents the problem in the form of a diagram*.

In addition to the immediate controlled factors, the behavior of some of the dependent variables are of great interest with respect to the observation of the thrust and other engine data. In the following a method is presented for the comprehensive determination of the transfer behavior of engines in general, particularly in the presence of various interferences. The method is

*For an explanation of the notation see pages 13 & 14.

demonstrated by the example of interference by the extraction of air behind the compressor.

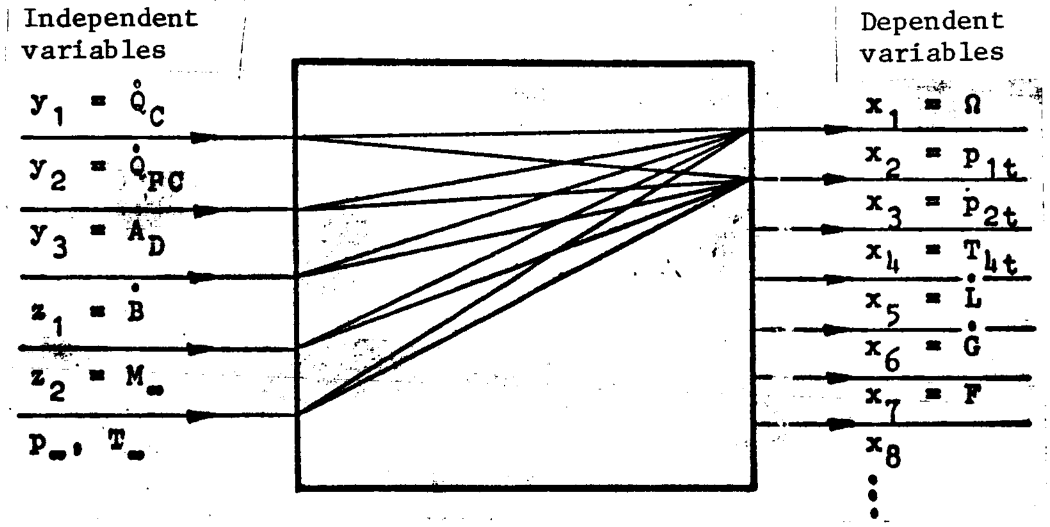


Figure 2. Turbojet Engine, Input and Output Values

3. Transfer Behavior of the Engine

The general form of the transfer function of jet engines may be given, with various simplifying assumptions, according to References (1, 2, and 3) in the following manner *. For instance, the transfer function of number of revolutions n and a gas temperature after the turbine T_{4t}, for a single-shaft engine with after-burner, adjustable thrust jet and compressor air extraction, is generally the following:

$$\frac{\Delta n}{n_o} = \frac{a_1}{1+\tau D}\frac{\Delta\dot{Q}_C}{\dot{Q}_{C_o}} + \frac{a_2}{1+\tau D}\frac{\Delta\dot{Q}_{PC}}{\dot{Q}_{PC_o}} + \frac{a_3}{1+\tau D}\frac{\Delta A_D}{A_{D_o}} + \frac{a_4}{1+\tau D}\frac{\Delta\dot{B}}{\dot{B}_o} \quad (1)$$

and

$$\frac{\Delta T_{4t}}{T_{4t_o}} = \frac{1+\tau_1 D}{1+\tau D}\, b_1 \frac{\Delta\dot{Q}_C}{\dot{Q}_{C_o}} + \frac{1+\tau_2 D}{1+\tau D}\, b_2 \frac{\Delta\dot{Q}_{PC}}{\dot{Q}_{PC_o}} + \frac{1+\tau_3 D}{1+\tau D}\, b_3 \frac{\Delta A_D}{A_{D_o}} + \frac{1+\tau_4 D}{1+\tau D}\, b_4 \frac{\Delta\dot{B}}{\dot{B}_o} \quad (2)$$

* References on page 14 and 15.

where $$\tau = -\frac{\Theta}{\left[\frac{\partial(\Delta M)}{\partial \Omega}\right]_{\dot{Q}_{C_o}, \dot{Q}_{PC_o}, A_{D_o}, \dot{B}_o}}$$ is a time constant

$$\tau_1 = -\frac{\Theta}{\left[\frac{\partial(\Delta M)}{\partial \Omega}\right]_{T_{4t_o}, \dot{Q}_{PC_o}, A_{D_o}, \dot{B}_o}}$$ is a time constant

etc.

$a_1 \ldots a_4$ and $b_1 \ldots b_4$ are constant coefficients.

ΔM: excess moment in an operating condition deflected from the inertial point P_o

Ω: angular velocity

$D = d/dt$: differential operator

Θ: inertia of rotor

The index 0 signifies the state of inertia.

The simplifying assumptions are: /5

a) slight variations in time of the input values, i.e. application of the theory of linear differential equations and validity of the principle of superimposition for all variations;

b) Use of the characteristic data of the stationary operating point for the calculation of nonstationary processes;

c) neglect of the time required for filling existing volumes, particularly the combustion chamber and the after-burner chamber, also neglect of the time lapse between fuel injection and the corresponding increase in enthalpy of the gas.

This actually determines the transfer functions of all of the dependent variables of an engine with respect to their form, however, the magnitudes of the constants a_1, a_2 ...; b_1, b_2 ...; etc. and of the time constants τ, τ_1 ..., remain unknown. They can be found only with the aid of the thermodynamic relationships of the engine.

3.2 Derivation of the Transfer Functions from Thermodynamic Relationships

A simple formulation of the desired transfer functions, i.e. the immediate numerical determination of the constants a_1, a_2...; b_1, b_2..., etc. and the time constant τ, τ_1..., from thermodynamical relationships is not feasible, particularly in the case of interferences, e.g. when air is extracted and the mass flow in the turbine and the compressor is unequal.

3.2.1 Relationships Derived from the Power Flow Diagram

A comprehensive description may be obtained in an unambigious manner of the behavior of the engine from an analysis of the heat or power flow diagram of the engine. Fig. 4 presents the power flow diagram of a turbojet engine with after-burner and air extraction for the case of nonstationary operation, established by utilizing the level designations shown in Fig. 3. In the diagram, sections A to L may be taken and the 11 equilibrium conditions may be formulated corresponding to Equations (3) to (13): /7

Section	Relationship	
A	$h_E = c_{p_1} T_{1t} - c_{p_\infty} T_\infty$	(3)
B	$h_K = c_{p_2} T_{2t} - c_{p_1} T_{1t}$	(4)
C	$\dot{L}\, h_{2t} = \dot{G}\, h_{2t} + \dot{B}\, h_{2t}$	(5)
D	$h_C = c_{p_3} T_{3t} - \dfrac{\dot{G}}{\dot{G}+\dot{Q}_C} c_{p_2} T_{2t}$	(6)
E	$h_T = c_{p_3} T_{3t} - c_{p_4} T_{4t}$	(7)
F	$h_{PC} = c_{p_{4b}} T_{4bt} - \dfrac{\dot{G}+\dot{Q}_C}{\dot{G}+\dot{Q}_C+\dot{Q}_{PC}} c_{p_4} T_{4t}$	(8)
G	$h_D = c_{p_{4b}} T_{4bt} - c_{p_5} T_5$	(9)
H	$h_C = \dfrac{1}{\dot{G}+\dot{Q}_C} \eta_C \dot{Q}_C Hu$	(10)
I	$(\dot{G}+\dot{Q}_C)\, \eta_m h_T = \dot{L}\, h_K + \Theta \dfrac{d(n^2/2)}{dt}$	(11)
K	$h_{PC} = \dfrac{1}{\dot{G}+\dot{Q}_C+\dot{Q}_{PC}} \eta_{PC} \dot{Q}_{PC} Hu$	(12)
L	$P_i = (\dot{G}+\dot{Q}_C+\dot{Q}_{PC})\, h_D - \dot{L}\, h_E$	(13)

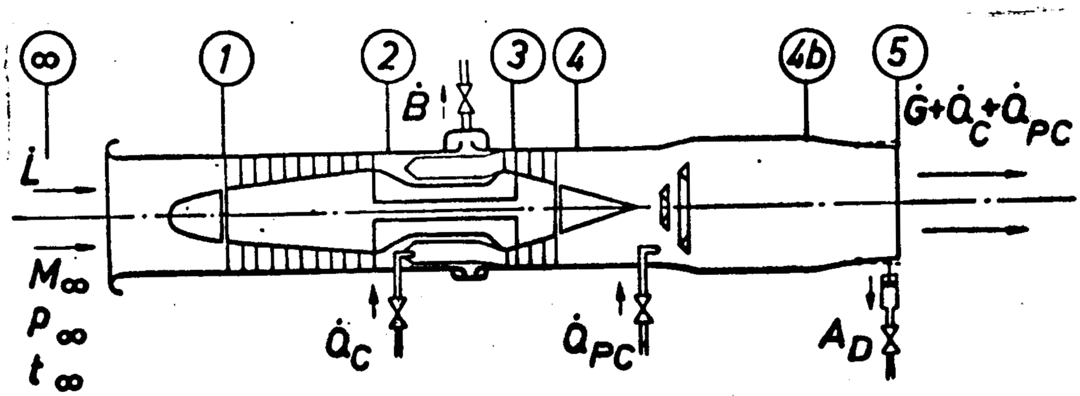


Figure 3. Single-Shaft Jet Engine with Afterburner, Adjustable Thrust Jet and Air Extraction, Establishment of the Engine Levels and Designation of the Independent Variables.

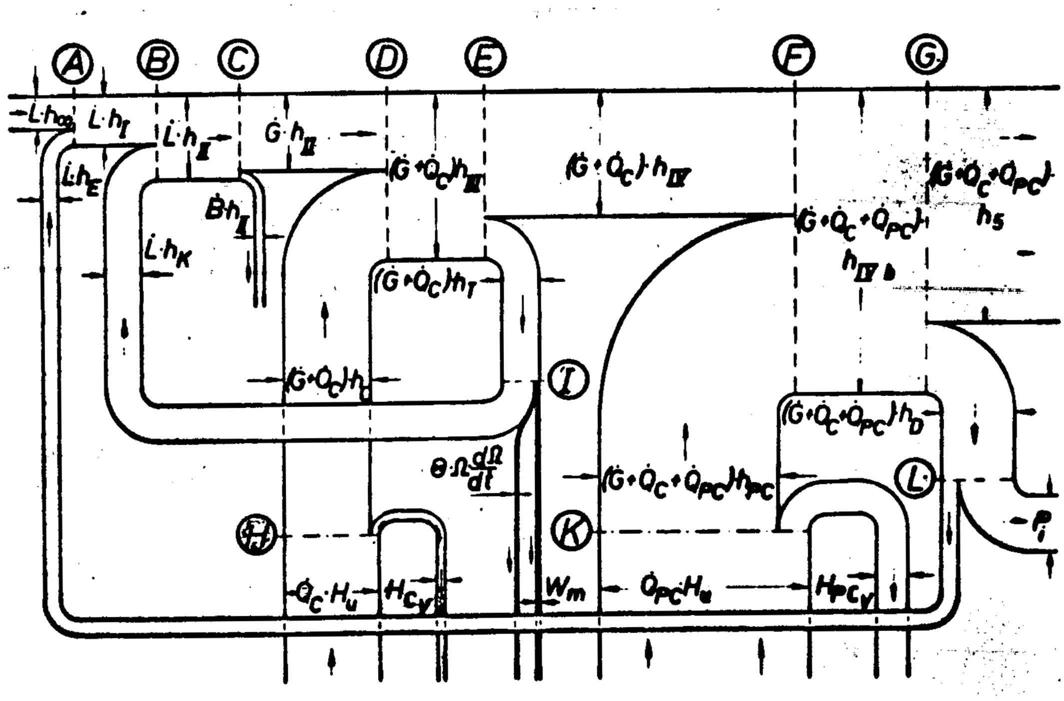


Figure 4. Power Flow Diagram of a Turbojet Engine with Afterburner and Air Extraction for the Case of Nonstationary Operation.

3.2.2 Interrelationship of the Enthalpy Differences with the Pressure Conditions and the Flight Mach Number /8

By relating the enthalpy differences as written above for the individual structural elements to the corresponding pressure conditions according to

Equations (14) to (17), the cyclic process may be closed through the equality of the products obtained from the compression and expansion pressure states, Equation (18).

$$h_E = \frac{1}{\eta_E} c_{p_E} T_\infty (\pi_E^{m_E} - 1) \tag{14}$$

$$h_K = \frac{1}{\eta_K} c_{p_K} T_{1t} (\pi_K^{m_K} - 1) \tag{15}$$

$$h_T = \eta_T c_{p_T} T_{3t} \left(1 - \frac{1}{\pi_T^{m_T}}\right) \tag{16}$$

$$h_D = \eta_D c_{p_D} T_{4bt} \left(1 - \frac{1}{\pi_D^{m_D}}\right) \tag{17}$$

$$m = \frac{\kappa - 1}{\kappa}$$

with

$$\pi_E \pi_K = \pi_C \pi_T \pi_{PC} \pi_D \tag{18}$$

In addition, the relationship between the back pressure enthalpy differences h_E and the flight Mach number M_∞ an independent variable, must be given

$$h_E = c_{p_\infty} T_\infty \frac{\kappa_\infty - 1}{2} M_\infty^2 \tag{19}$$

3.2.3 The Flow Behavior of the Structural Groups of the Engine /9

Information concerning the behavior of the engine in the case of a deflection from the stationary operating state is still missing. This information is given by the flow behavior of structural groups having throttling functions: the compressor, the turbine and the thrust jet. In the case of supersonic velocities the inlet must also be taken into consideration.

With slight standard deviations from the inertial point, which is designated by the index "0", the mass flow through the compressor may be given as follows:

$$\frac{\dot{L}}{\dot{L}_0} = \left(\frac{\Omega}{\Omega_0}\right)^\alpha \left(\frac{\pi_K}{\pi_{K_0}}\right)^\beta \tag{20}$$

The mass flow through the turbine is a function of the pressure ratio π_T and the gas temperature T_{3t}, as long as no sonic velocity occurs in the wheels. When the velocity of sound is reached, the flow depends only on the pressure p_{3t} and the temperature T_{3t}. In a very general manner, the mass flow through a single- or multiple-stage turbine may be expressed by

$$\frac{\dot{G}+\dot{Q}_C}{\dot{G}_o+\dot{Q}_{C_o}} = \frac{p_{3t}}{p_{3t_o}}\sqrt{\frac{T_{3t_o}}{T_{3t}}}\,E \qquad (21)$$

The so-called elliptic factor E can be given as a function of π_T. If at the outlet of the turbine lead wheel sonic velocities are obtained, which often occurs in the vicinity of the design point, E = 1. The pressure ratio P_{3t}/P_{3to} in Equation (21) may be replaced by the partial pressure ratio. Then, from (21)

$$\frac{\dot{G}+\dot{Q}_C}{\dot{G}_o+\dot{Q}_{C_o}} = \frac{\pi_E\pi_K\pi_C}{\pi_{E_o}\;\pi_{K_o}\;\pi_{C_o}}\sqrt{\frac{T_{3t_o}}{T_{3t}}}\,E \qquad (21.1)$$

Let us here introduce the simplification that for slight standard deviations, the pressure ratios in the inlet, the combustion chamber and the afterburner chamber are according to

$$\begin{aligned}&\pi_E = \pi_{E_o} = \text{const} ; \qquad \pi_C = \pi_{C_o} = \text{const} ;\\ &\pi_{PC} = \pi_{PC_o} = \text{const}\end{aligned} \qquad (22)$$

or, e.g.

$$\pi_C = \pi_{C_o} = \frac{p_{2t}}{p_{3t}} = \frac{p_{2t_o}}{p_{3t_o}} \quad \text{or} \quad \frac{p_{2t}}{p_{2t_o}} = \frac{p_{3t}}{p_{3t_o}}$$

This means that the pressure losses expressed in this manner increase or decrease linearly with the existing pressure level. With this simplification, Equation (21.1) may be written as

$$\frac{\dot{G}+\dot{Q}_C}{\dot{G}_o+\dot{Q}_{C_o}} = \frac{\pi_K}{\pi_{K_o}}\sqrt{\frac{T_{3t_o}}{T_{3t}}}\,E \qquad (21.2)$$

Finally, for the mass flow through the thrust jet the following expression is valid:

$$\frac{\dot{G}+\dot{Q}_C+\dot{Q}_{PC}}{\dot{G}_o+\dot{Q}_{C_o}+\dot{Q}_{PC_o}} = \frac{A_D}{A_{D_o}}\,\frac{p_5}{p_{5_o}}\,\frac{T_{5_o}}{T_5}\sqrt{\frac{h_D}{h_{D_o}}} \qquad (23)$$

For a hypercritical expansion pressure ratio we obtain by the introduction of the partial pressure ratio and with consideration of the simplifications according to Equation (22)

$$\frac{\dot{G}+\dot{Q}_C+\dot{Q}_{PC}}{\dot{G}_o+\dot{Q}_{C_o}+\dot{Q}_{PC_o}} = \frac{A_D}{A_{D_o}} \frac{\pi_T}{\pi_{T_o}} \frac{\pi_K}{\pi_{K_o}} \sqrt{\frac{T_{4bt_o}}{T_{4bt}}} \qquad (23.1)$$

With this, in the case of the present example we have a system of 20 equations and 20 dependent variables and four independent variables ($\dot{Q}_C$, $\dot{Q}_{PC}$, A_D, $\dot{B}$), not including M_∞, p_∞, and T_∞. In principle, the system can thus be solved.

3.2.4 Engine Thrust /11

In addition to the foregoing, any further pertinent characteristic of the engine may now be given, such as the thrust, the specific fuel consumption, the internal efficiency, etc., and included in the solution of the system without affecting the system of equations, provided that the values can be expressed with the dependent and independent variables already introduced. For instance, the thrust is given by

$$F = (\dot{G}+\dot{Q}_C+\dot{Q}_{PC}) \sqrt{2\, h_D} - \dot{L}\sqrt{\kappa_\infty R\, T_\infty}\, M_\infty \qquad (24)$$

3.3 Linearization and Solution of the System

If the investigation is restricted to small deviations from the stationary operating point, the system of equations may be linearized. It is readily solved by matrix calculations. Relationships similar in form to those generally given in Equations (1) and (2) are immediately obtained between all dependent and independent variables. In the case of greater variations, the calculations may be performed in several stages.

3.4 An Example of Evaluation: the SNECMA ATAR F Engine

3.4.1 The Transfer Functions

An evaluation was performed on the example of the SNECMA ATAR F after-burner engine. The following transfer functions of number of revolutions n and gas temperature after the turbine T_{4t} for a flight Mach number $M_\infty = 0$ and a height of $H_\infty = 0$, for a nominal number of revolutions.

$$\frac{\Delta n}{n} = \frac{0{,}449}{1+\tau D} \frac{\Delta \dot{Q}_C}{\dot{Q}_{C_o}} - \frac{0{,}161}{1+\tau D} \frac{\Delta \dot{Q}_{PC}}{\dot{Q}_{PC_o}} + \frac{0{,}835}{1+\tau D} \frac{\Delta A_D}{A_{D_o}} - \frac{0{,}00251\ \dot{B}_o}{1+\tau D} \frac{\Delta \dot{B}}{\dot{B}_o} \qquad (25)$$ /12

$$\frac{\Delta T_{4t}}{T_{4t}} = \frac{0{,}298+0{,}645\cdot\tau D}{1+\tau D}\,\frac{\Delta\dot{Q}_C}{\dot{Q}_{C_o}} + \frac{0{,}157+0{,}0321\cdot\tau D}{1+\tau D}\,\frac{\Delta\dot{Q}_{PC}}{\dot{Q}_{PC_o}} - \frac{0{,}814+0{,}166\cdot\tau D}{1+\tau D}\,\frac{\Delta A_D}{A_{D_o}} + \frac{(0{,}0111+0{,}00916\cdot\tau D)\dot{B}_o}{1+\tau D}\,\frac{\Delta\dot{B}}{\dot{B}_o} \qquad (26)$$

with $\tau = 0.733$ sec.

3.4.2 Transition Functions

Figure 5 contains a representation of the progress in time of the dependent variables in the case of e.g. an abrupt input of $\Delta\dot{B} = 1$ kg/sec. The transition functions of all of the independent variables with respect to the example are entered. Particularly interesting are the progress and the final values of the variations of the number of revolutions n and the gas temperatures T_{3t}, T_{4t}, T_{4bt}, T_5 with respect to the mechanical behavior and the life of the engine, also the variation of the pressure ratio Π_K and the air flow $\dot{L}$ for the fixation of the shift of the operating point in the characteristic field of the compressor, although the results are valid only for the engine without control, i.e. for the case when all three governing values are simultaneously constant. Finally, the progress of the thrust is also remarkable.

3.4.3 Representation of the results in the Characteristic Field of the Compressor

The shift of an inertial point P_o in the characteristic field of the compressor is shown together with the progress of the variation for the discontinuous functions of all independent variables. Fig. 6 presents the deflection of the operating point for certain changes in magnitude of the compressor air extraction, fuel supply and thrust jet cross-section, without the afterburner. Fig. 7 shows a variation in the fuel supply to the afterburner during operation of the latter. The following should be noted in connection with the figures:

a) The deflection of the inertial point due to air extraction is different for operation without or with an operational afterburner. Since when air is being extracted the flow of gas is reduced in the afterburner also, an apparent increase of the fuel supply to the afterburner is superimposed, be- /15
cause the fuel supply remains constant.

b) When the fuel flow to the main combustion chamber is increased, a good fit to the operating curve results only in the case of operation without the afterburner.

c) The deflection of the operating point in exactly opposite directions when the fuel supply of the afterburner is increased, or the cross section of the jet is made larger, represents a control with respect to the accuracy of the calculation.

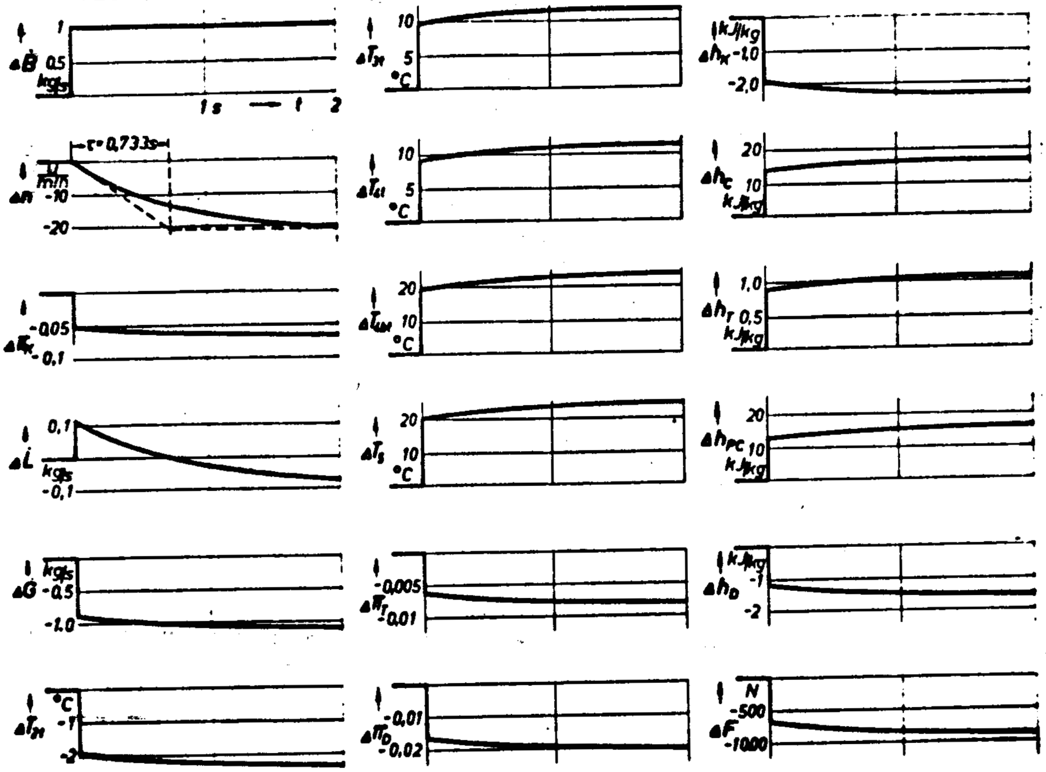


Figure 5. Transition Functions of the ATAR F Engine with Air Extraction, Afterburner Operational. /13

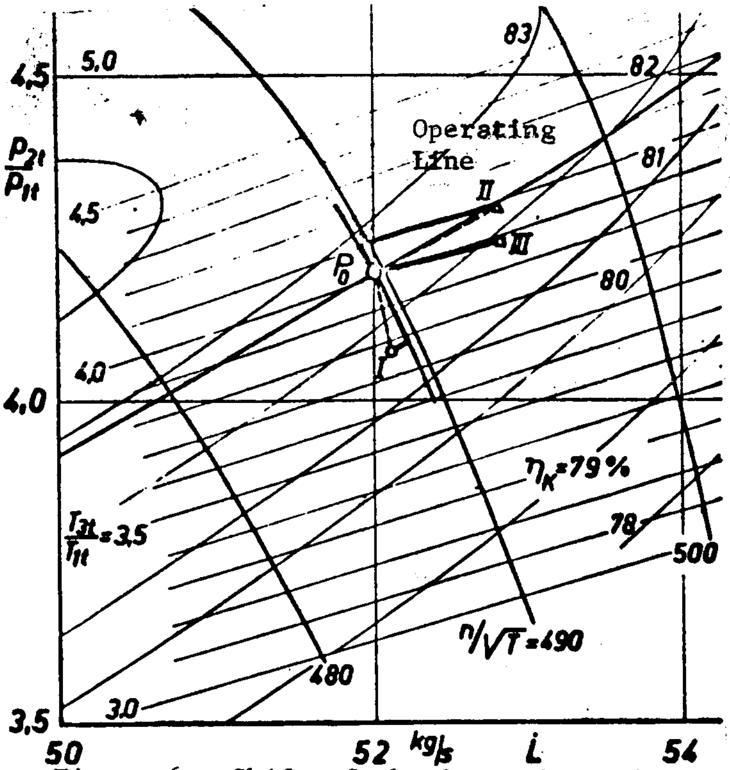
3.5 Notes Concerning the Application of the Procedure

3.5.1 Data Required for Evaluation

In order to evaluate the system of equations, knowledge of the characteristic field of the compressor is necessary; the exponents α and β of Equations (20) may then be determined for the vicinity of the inertial point to be investigated. For the rest, only the data concerning the state, i.e. temperatures, pressures and efficiencies of the individual structural groups, the number of revolutions, the mass flow and the moment of inertia of the rotor are required.

3.5.2 Possible Extensions

The system of equations can be solved very readily and rapidly with the aid of matrix calculations. It is therefore not necessary to bring the system into a more compact form through the elimination of certain equations and unknowns. In addition, in the form presented, the accuracy of the investigation can be increased simply by the addition of further relationships (e.g. for efficiency variations within the individual stages of the computation or by



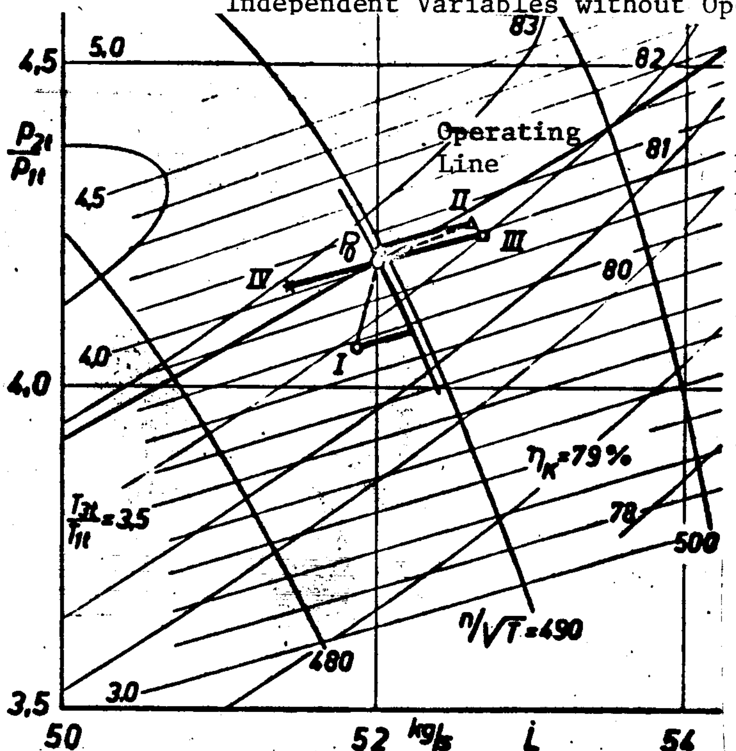
Deflection of the operating point ....P_o

I.....with air extraction ($\Delta\dot{B}$ = 2 kg/sec.),

II....with increasing fuel supply to the main combustion chamber ($\Delta\dot{Q}_C$ = 0.04 kg/sec.),

III...with increasing thrust jet cross sections (ΔA_D = 0.003 m^2)

Figure 6. Shift of the Operating Point P_o with Variations of the Various Independent Variables without Operating Afterburner



Deflection of the operating point...........P_o

I.....with air extraction ($\Delta\dot{B}$ = 2 kg/sec.),

II....with increasing fuel supply to the main combustion chamber ($\Delta\dot{Q}_C$ = 0.04 kg/sec.),

III...with increasing thrust jet cross sections (ΔA_C = 0.003 m^2).

IV...with increasing fuel supply to the afterburner ($\Delta\dot{Q}_{PC}$ = 0.05 kg/sec.).

Figure 7. Shift of the Operating Point P_o with Variations of the Various Independent Variables with Operating Afterburner.

taking into consideration the fill times of the existing volumes). This can be accomplished without interfering with the convenience of the solution.

The extension of the method to the investigation of two-shaft engines and two-cycle engines causes no fundamental difficulties. /16

For instance, to investigate a two-shaft turbojet engine, it is merely necessary to write Equations (4), (7), (11), (15), (16), (20) and (21.2) for a second time for the second rotor aggregate, Equation (18) in an extended form and the other equations with suitably changed indices.

A possible representation of the relationships in the form with reduced quantities (independent of external pressure and temperature) was purposely omitted in the interest of clarity.

4. Behavior of the Control Circuit

Since the transfer behavior of the control train is now known in detail, the closed contol circuit may be presented. It is feasible both to design suitable controls or to investigate an existing control system together with the engine with respect to favorable control behavior during interference with the installation. Such problems are readily solved with the aid of an analog computer in which either the complete regulatory system, or because of the limited volume of the computer, frequently only the essential control factors of the engine are represented simultaneously. It is also possible, however, to ask for the progress of the remaining pertinent dependent variables in sequence, with a single control setting, so that complete information may be gained with respect to the dynamic behavior of the closed engine control circuit.

5. Summary same as Abstract. /17

6. Appendix /18

6.1 Notation and Indices

1.	a		Coefficient
2.	A	m^2	Area
3.	b		Coefficient
4.	$\dot{B}$	kg/s	Extraction air flow
5.	c		Coefficient
6.	D	d/dt	Differential operator
7.	E		Elliptic factor
8.	F	N	Thrust
9.	$\dot{G}$	kg/s	Gas flow
10.	h	kJ/kg	Specific Enthalpy
11.	Hu	kJ/kg	Lower heat value
12.	$\dot{L}$	kg/s	Air flow
13.	m	$\frac{k-1}{k}$	Ratio
14.	M		Mach number
15.	ΔM	Nm	Excess moment
16.	n	U/min	Number of revolutions

17.	p	N/m^2	Pressure
18.	P	W	Power
19.	P		Operating point
20.	$\dot{Q}$	kg/s	Fuel flow
21.	R	J/kg °K	Gas constant
22.	T	°K	Temperature
23.	w		Governing factor
24.	x		Control factor
25.	y		Set value
26.	z		Interfering factor
27.	α		Exponents from the characteristic field
28.	β		Of the compressor
29.	Δ		Slight variation
30.	η		Efficiency
31.	θ	$kg.m^2$	Inertia of rotor
32.	k		Isotropic exponent
33.	π		Pressure ratio
34.	τ	s	Time constant
35.	Ω	1/s	Angular velocity
36.	I to IV		Operating points

Indices /19

C	Combustion chamber
D	Thrust jet
E	Inlet
i	Internal
K	Compressor
m	Mechanical
PC	Afterburner
t	Total
T	Turbine
0	Inertia
1	Before the compressor
2	After the compressor
3	Before the turbine
4	After the turbine
4b	After the afterburner
5	End of thrust jet
..	Environment

6.2 References /20

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